SCI

APPLICATION OF SDMA

Wireless Communication Systems

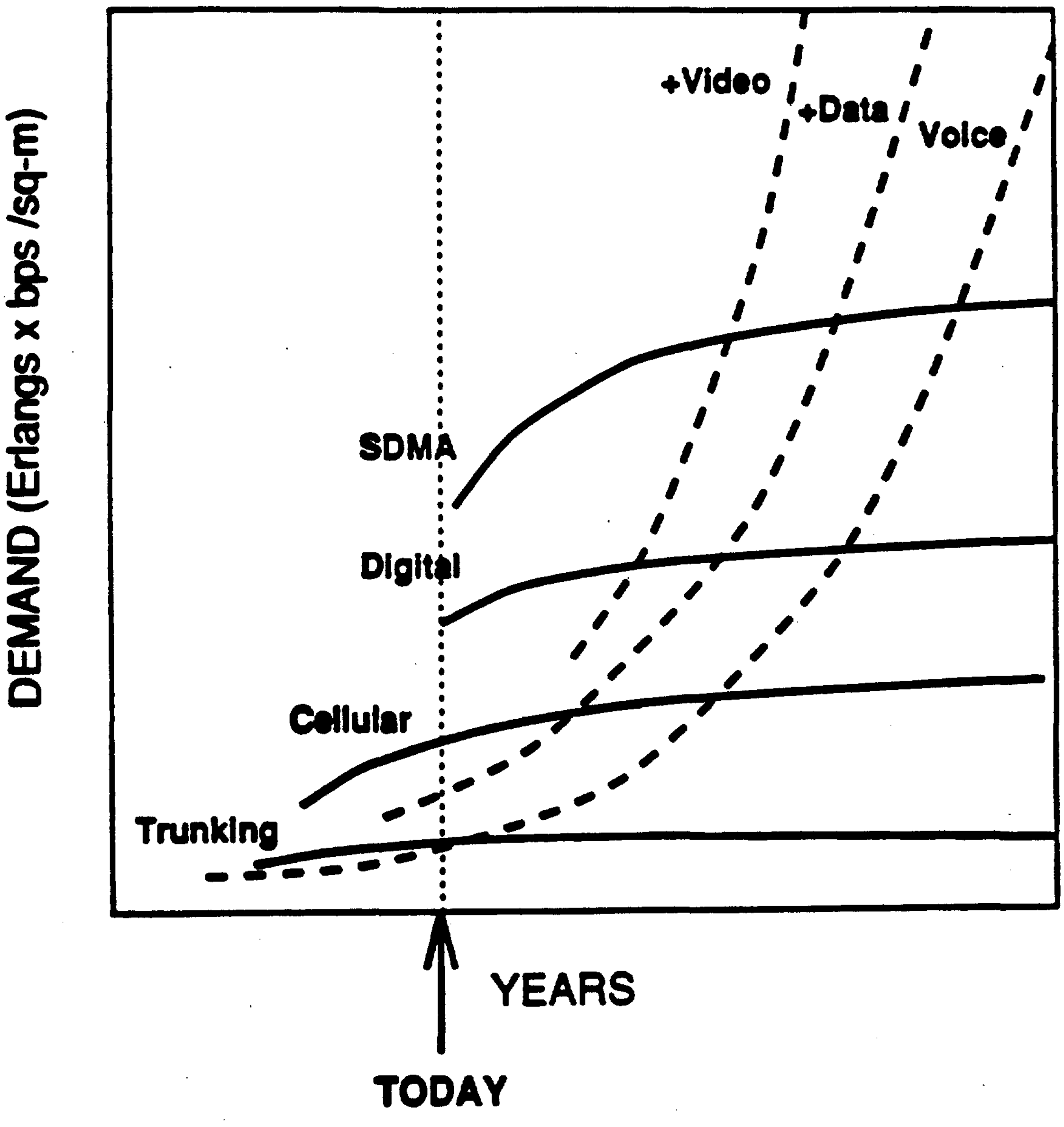
FUNDAMENTAL TECHNOLOGIES
FOR
INCREASING SPECTRAL EFFICIENCY

- Frequency Reuse with Time
  - Trunking
- Frequency Reuse with Space
  - Cellular Architecture
- Efficient Channel and Source Coding
- SPATIAL DIVISION MULTIPLE ACCESS

APPLICATION OF SDMA

Wireless Communication Systems

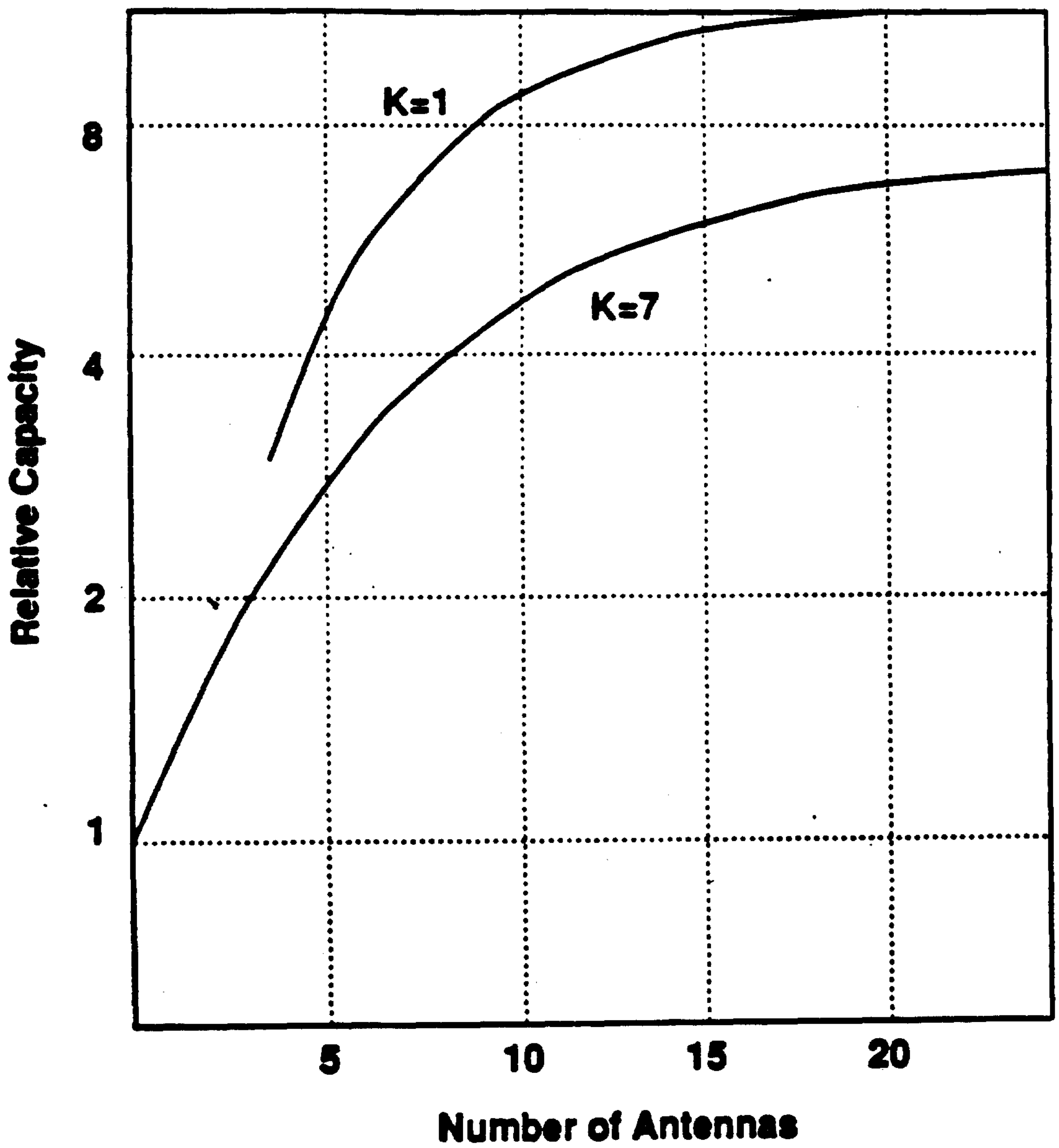
WIRELESS EVOLUTION



APPLICATION OF SDMA

Wireless Communication Systems

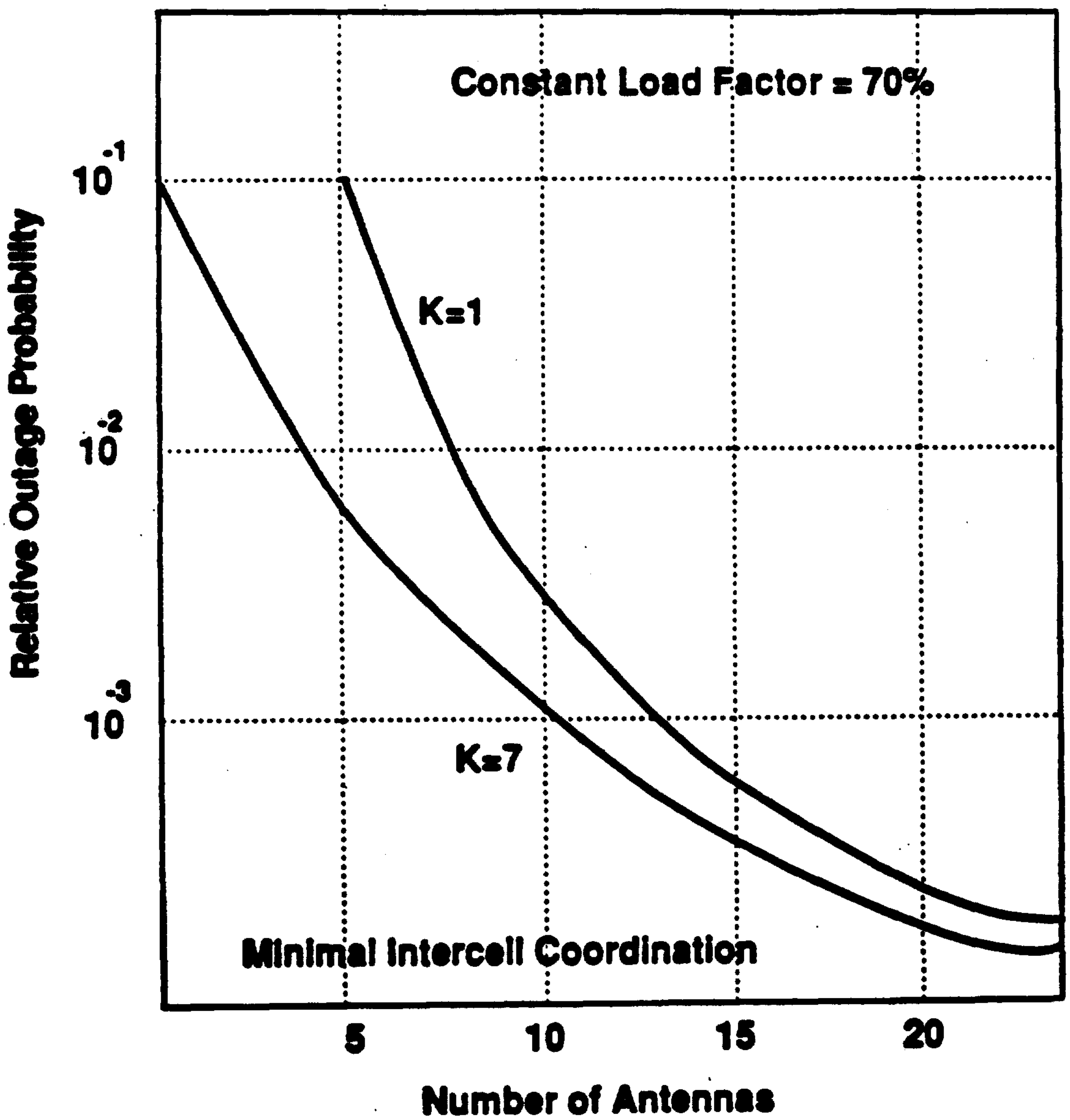
Capacity Improvement with Number of Antennas



APPLICATION OF SDMA

Wireless Communication Systems

OUTAGE PROBABILITY IMPROVEMENT



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OTHER APPLICATIONS OF SDMA

Wireless Communication Systems

- Commercial air-to-ground communication systems
- Cellular mobile communication systems
- Satellite communications
- Private/Public Land Mobile Radio (PLMR/SMR) communication systems
- Wireless Local Area Networks (LANs)
- Wireless broadcast systems (e.g., HDTV, DAB)
- Surveillance systems

• • •

MAKING SDMA A REALITY

The Role of a Pioneer's Preference

- SDMA is a fundamentally new technology which can significantly increase capacity and enhance quality.
- SDMA will be required to meet the rapidly growing demand for wireless access.
- SDMA can allow next generation systems to coexist with incumbant users of RF frequency bands.
- SDMAs efficacy has been demonstrated theoretically and experimentally.
- A Pioneer's Preference will enable SCI to establish SDMA in the wireless marketplace.

Exhibit D

ALL STATE LEGAL SUPPLY CO. 1-800-222-0510 EDR11 RECYCLED

EXHIBIT D

ArrayComm

SDMA-EXP-93-001

SDMA Technology

Experimental Results

File Number: S-1193-EX-93
Call Sign: KS2XAG

13 September 1993

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This is document 17 of 20.

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CONTENTS

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1. Introduction

This report is intended to document results of initial testing of ArrayComm's SDMA (Spatial Division Multiple Access) technology performed under Special Temporary Authority (STA) granted by the FCC on 23 July 1993 (call sign KS2XAG). The purpose of these tests was to perform system integration and debugging as well as preliminary low-power demonstrations of the efficacy of SDMA technology.

SDMA system integration was completed and initial tests begun ahead of schedule on July 23. The initial tests have successfully demonstrated the ability of SDMA technology to improve the quality and capacity of wireless communications systems in general. Though the tests results described herein were achieved using standard (AMPS) analog cellular technology, SDMA can provide similar improvements for digital formats as well, since the technology is modulation independent. While the results may seem impressive, more testing is required before concrete conclusions with regard to particular applications can be drawn.

The information contained in this report and the video tape provided herewith are the property of ArrayComm, Inc. Due to the highly competitive nature of the wireless communication business, we hereby request the information contained in the body of this report and the video tape be kept confidential. An abstract for general release is provided in Appendix B.

2. Executive Summary

This report describes the results of recent experimentation conducted by ArrayComm, Inc., of its proprietary and patented SDMA technology. Using standard AMPS analog handsets and SDMA base station equipment constructed from standard components to ArrayComm's specifications, the efficacy of SDMA technology has been demonstrated. In particular, the following important attributes of ArrayComm's SDMA technology have been successfully demonstrated:

- SDMA signal processing gain, leading to improved signal quality, lower handset powers, and larger coverage areas from SDMA base stations compared to conventional base stations,
- SDMA spatial demultiplexing, leading to interference rejection and the ability to receive signals from multiple mobile units on the same frequency at the same time,
- SDMA spatial multiplexing, the ability to directionally and selectively transmit RF energy toward intended mobile units to the exclusion of others on the same frequency at the same time, including users of other systems (*e.g.,* microwave users in PCS bands), and consequently
- SDMAs ability to simultaneously communicate with multiple mobile units on the same frequency at the same time from the same base station, independent of modulation

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format, thus leading to a substantial improvement in spectral efficiency over current systems.

The video presentation provided with the report documents each of these points. The experiments conducted and shown during the course of the video demonstrations are quite possibly unique. Full-duplex communications between multiple mobile units and a single base station on the same frequency at the same time have not been documented anywhere else known to date. While the ability to do so may be counterintuitive to most, it is most assuredly possible.

The applications of SDMA technology are numerous. In general, SDMA is an enabling technology which, through intelligent use of antenna arrays and standard signal processing components, substantially improves the quality, capacity, and cost effectiveness of wireless communication systems. As wireless becomes a predominant mode in the worldwide communications market, the spectral efficiency provided by SDMA technology will be in ever-increasing demand.

For example, in the implementation of next generation PCS systems, fixed-cost savings of between 30% to 70% over non-SDMA implementations are possible, not to mention the dramatic reduction in recurring costs (maintenance). Furthermore, SDMA technology provides information to operators of such systems which allows for *new services* to be provided. In particular, with knowledge of the user's location, a substantial number of valuable position-related services can be offered, including determining the origin of emergency calls, locating stolen vechicles, and providing other information services such as the location of the nearest gas station.

While the fundamental concepts behind SDMA technology have been demonstrated and documented herein, a substantial amount of further experimentation remains. In the future, longer range tests will be conducted, and the effects of various RF propagation environments characterized.

3. Background

ArrayComm's SDMA technology promises to improve spectral efficiency many-fold by allowing multiple portable/mobile wireless transceivers to occupy the same frequency simultaneously, being discriminated on the basis of location by the base station. In a sense, this is the ultimate in frequency re-use; the ability not only to use the same frequency in adjacent cells, but to re-use it in the *same* cell. By employing *smart antennas*, users are tracked, allowing substantial reductions in transmitted power from both the base stations and the portable units (reduction of *RF pollution*), in addition to allowing for a completely new class of position related services to be provided to the consumer. In addition, the problem of coexistence with incumbent microwave users which next generation PCS operators face can be mitigated with SDMA technology as indicated in the accompanying figures.

SDMA technology was developed by the principals of ArrayComm while they were affiliated with Stanford University. ArrayComm is currently attempting to commercialize the SDMA technology. Since ArrayComm's inception, Mr. Martin Cooper has spearhead the commercialization effort as its chairman and CEO. Mr. Cooper headed Motorola's entry in to the cellular, two-way radio, and paging businesses during an illustrious career there. He has been instrumental in introducing the technology to many of the domestic companies currently involved in one way or another with wireless telecommunications.

Most of the major companies which have been exposed to the technology have indicated substantial interest in seeing the successful completion of our preliminary test phase. These companies include Bell Atlantic, BellSouth, GTE Airfone, PageNet, PacTel, GTE MobileNet, Ameritech, Southwestern Bell, Db Products, Mark Antennas, Watkins-Johnson, and others. In particular, PacTel and the Bay Area Cellular Telephone Company (BACTC), the local non-wireline cellular carrier, are cooperating with ArrayComm during these tests.

4. Preliminary SDMA Experimentation

This section describes some of the preliminary tests of ArrayComm's SDMA technology which have been conducted along with the results that have been obtained to date. The initial experimental objectives are discussed followed by an overview of the experimental apparatus. While the results are described qualitatively for the most part herein, a video tape has been prepared and is included with the filing.

4.1 Objectives

During the initial phases of SDMA experimentation, the basic objective is to demonstrate the fundamental principles of SDMA technology using standard communications equipment and protocols. To that end, off-the-shelf AMPS handsets are used and the system is tuned to the appropriate US cellular frequencies. The objective of the initial tests is to demonstrate the ability of SDMA technology to:

1. track multiple users on the same channel in the same cell,
2. improve signal quality from all users simultaneously through directional reception,
3. directionally transmit different signals to each user simultaneously on the same frequency channel, thereby demonstrating the ability to
4. increase system capacity.

Improved signal quality is achieved through intelligent signal processing, and demonstrably increases the range over which signals from mobile units can be successfully demodulated. Improved capacity is a consequence of the ability to simultaneously receive from and transmit to multiple mobile units on the same channel (in this case frequency), an ability similarly achieved through intelligent signal processing. Both of these are achievable due to the fact that the SDMA processor can track multiple cochannel units in real time.

4.2 Experimental Apparatus

Initial SDMA experimentation employed the following equipment:

1. standard AMPS cellular telephones,
2. 20 dB pads for attenuating signals transmitted by the phones (to simulate longer-range transmission),
3. antenna array built by Db Products to ArrayComm's specifications,
4. standard cellular transceivers built to ArrayComm's specifications by Watkins-Johnson,
5. ArrayComm's SDMA processor for performing the intelligent signal processing required,
6. an audio processing board for performing standard AMPS signal processing (SAT tone filtering, emphasis, *etc.*) for multiple AMPS channels,
7. a RF communications analyzer for call initiation,
8. spectrum analyzers and portable receivers for assessing SDMA's directive transmission ability, and
9. a network computing environment for experiment control and data storage.

A block diagram of the basic system is shown in Figure 4-1. By employing standard cellular duplexers behind each element in the antenna array, a single array could be used. The transceivers were constructed with off-the-shelf RF components, and the interface to the SDMA transmitters and receivers employed standard A/D and D/A converters. The receivers are tunable to any 200 kHz frequency span in the cellular uplink band (824 MHz – 849 MHz) and similarly the transmitters are tunable to any 200 kHz frequency span in the cellular downlink band (869 MHz – 894 MHz). This bandwidth encompasses six (6) contiguous 30 kHz AMPS channels and allows the SDMA prototype to perform frequency hand-offs when users cross paths.

The SDMA receivers and transmitters were built by ArrayComm. They were constructed with standard digital signal processing components; no special purpose DSP chips were required. These boards implement the spatial multiplexing and demultiplexing functions under the control of the SDMA processor. The audio processing board was constructed using available AMPS signal processing components and has the capability to simultaneously process four (4) audio channels. The SDMA processor consists of a standard single-board computer (SBC) on which much of the intelligent (proprietary) signal processing is performed. The operator interface to the SBC is through an ethernet link to a workstation network not shown in Figure 4-1.

4.3 Experimental Parameters

The relevant parameters of the initial SDMA tests are summarized in Table 4-1.

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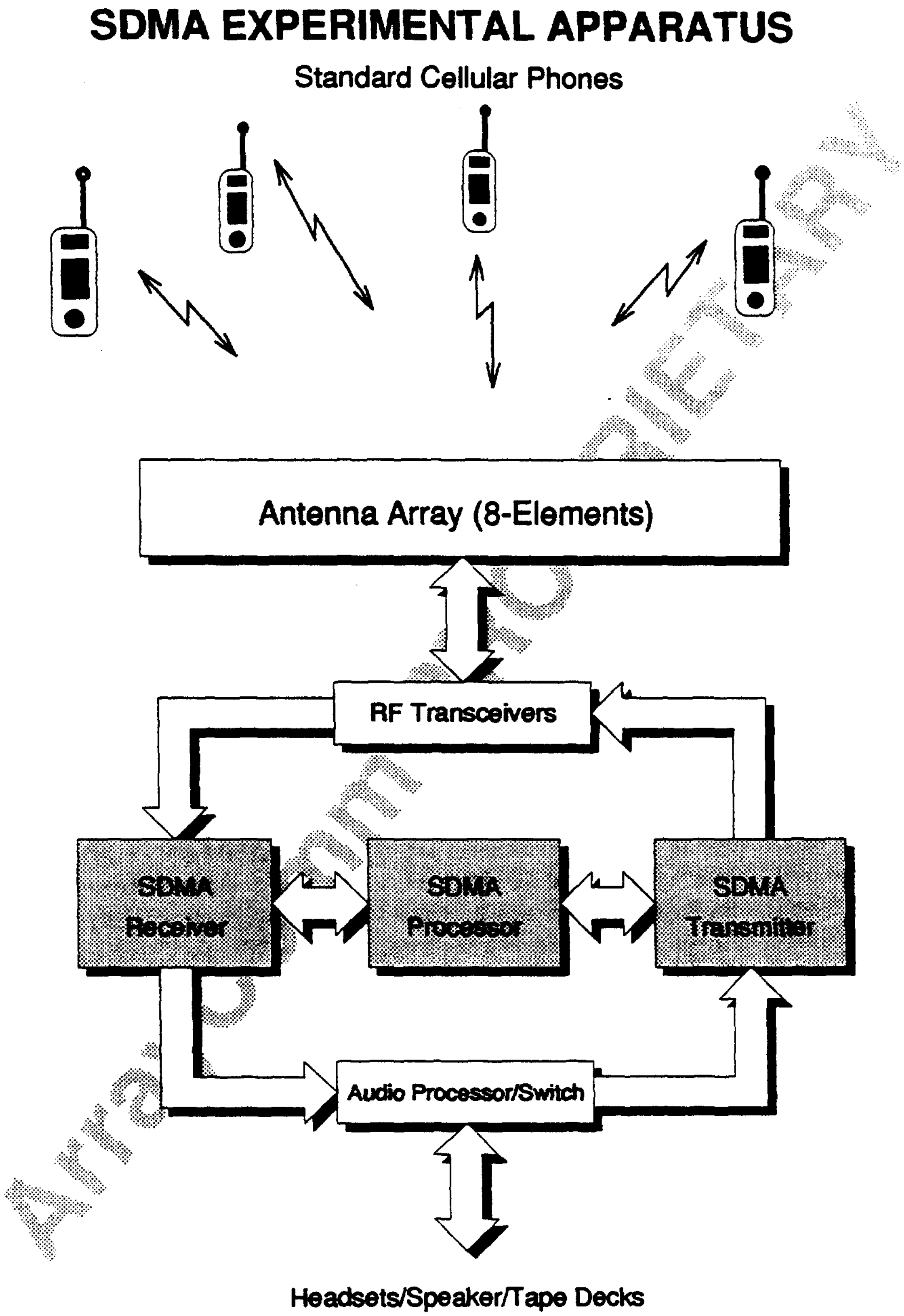

Figure 4-1: Block Diagram of ArrayComm's SDMA Prototype System

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Summary of SDMA Prototype Experimental Parameters

Frequency Bands	824 – 849 MHz 869 – 894 MHz
Initial Frequencies	$825.09, 825.24$ MHz $870.09, 870.24$ MHz
Channel Width	30 kHz IS-3 AMPS
Modulation	IS-3 AMPS FM
Portable Units Tx Power	 8 dBm
SDMA Base Station ERP Antenna Height	 -8 dBm 3.3 m above local terrain

Table 4-1: ArrayComm's SDMA Prototype System Parameters

4.4 Experimental Procedure

Initial experimentation was performed in the vicinity of ArrayComm's main offices. The antenna array was mounted on a portable tower at a height of approximately 3.3 m above the local terrain. Up to four handsets have currently been employed, each set to the same frequency channel (channels 3 and/or 8 in the cellular band) at the lowest possible transmit power level of 8 dBm by the HP8920A. Each cellular handset is programmed with a foreign SID so as not to interfere with local cellular operations. The SDMA base station transmits the appropriate SAT tone to keep the channels active in the portables at all times during the test. The initial ranges between the SDMA base station and the handsets were kept less than 200 m. These ranges included scenarios in which the line-of-sight from the phone to the array was occluded by foliage as well as two-story commercial buildings. The initial transmit powers were less than -26 dBm per antenna, ensuring a maximum ERP of -8 dBm.

Signal quality improvement and range extension were first demonstrated using a single cellular phone. The phone was set to 825.24 MHz and its lowest power setting (8 dBm) and a 20 dB attenuator inserted in the antenna to simulate longer range transmission. Signals from each of the antenna elements were recorded as a function of range from the base station as well as the output of the SDMA processor. From these data, the SDMA processor output could be compared to the output of any individual element or combination thereof. A longer range test was also conducted without the 20 dB attenuator by carrying the phone to greater distances from the array, including occlusion of line-of-sight by trees and buildings.

Capacity improvement was demonstrated by setting up multiple handsets on the same channel at the same time, and successfully transmitting signals to and from these mobile units while they were in motion. While the volumes of data generated by such an experiment are difficult to include in a report, the video presentation clearly demonstrates this capability. To further quantify the performance of the system in this regard, a short burst of signals from

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the antennas were stored in addition to the outputs of the SDMA processor. Subsequent data analysis was performed to show the C/I improvement possible with SDMA.

To quantify SDMA's directional transmission capability, a single phone was placed on the air. While keeping the phone stationary, an antenna and RF spectrum analyzer were used to measure the SDMA base station transmitted power as a function of angle at the same range and height as the phone. A second phone was added and the ability to selectively isolate users from transmissions intended for others on the same channel in the same cell was demonstrated. This clearly demonstrated the ability of the SDMA processor and spatial multiplexer to focus energy in particular directions to the exclusion of others. This is necessary, otherwise the SDMA base station's transmission to that user would interfere with similar transmissions intended for other users on the same frequency at the same time.

4.5 Experimental Results

4.5.1 SDMA Signal Processing Gain

The results of initial SDMA experimentation verify that indeed an improvement in signal quality approximately equal to the theoretical gain ($10 \log_{10} M$ where M is the number of antenna elements in the array) under ideal conditions is achievable in most situations. This is shown in Figure 4-2 where a mean SDMA processing gain in excess of $9\,dB$ is clearly manifest.[1] For this experiment, a sample rate of $71.4\,kHz$ was used, and 512 consecutive snapshots were collected for the calculations at each range.

The upper plot shows the signal-to-noise ratios (SNRs) for the indicated outputs; the lower plot shows the relative improvement in dB of the SDMA processor output compared to each of the others. The *Mean Single Element SNR* was computed as the average power from all eight antenna elements. This partially accounts for the fact that compared to the coherent SDMA Output SNR, the improvement can actually exceed the theoretical value in the *ideal* case. The *Two-Antenna Diversity SNR* is the SNR which would be achieved using a two-element diversity scheme similar to that currently employed at some cell sites in the AMPS cellular system. Here, the maximum signal strength of the two outer elements $1.26\,m$ apart is chosen as the reference.

Due to the complexity of the RF environment in the vicinity of the array (cars, trees, *etc.*), sufficient scattering was present to substantially perturb the element output powers which would otherwise have all been equal. Therefore, as noted above, the SDMA processing gain over a single element depends upon the element chosen as a reference. The *Minimum/Maximum SDMA Gain* results from chosing the maximum/minimum single element output as the reference. The *Diversity SDMA Gain* is that which would be achieved over the standard two-element diversity system described above. The *Mean SDMA Gain* is the SDMA improvement over the average power from all eight elements.

A demonstration of the fact that this improvement is available at greater distances and when there is no line-of-sight is shown in Figure 4-2 as well. While the first segment (approximately out to $80\,m$ range) is nearly line-of-sight, the second segment involves power measurements when there was no longer a line-of-sight to the array. In addition to a stand

[1]SDMA's processing gain is in addition to that provided by a single antenna element which, as a consequence perhaps of elevation shaping, could have 10 dBi gain.

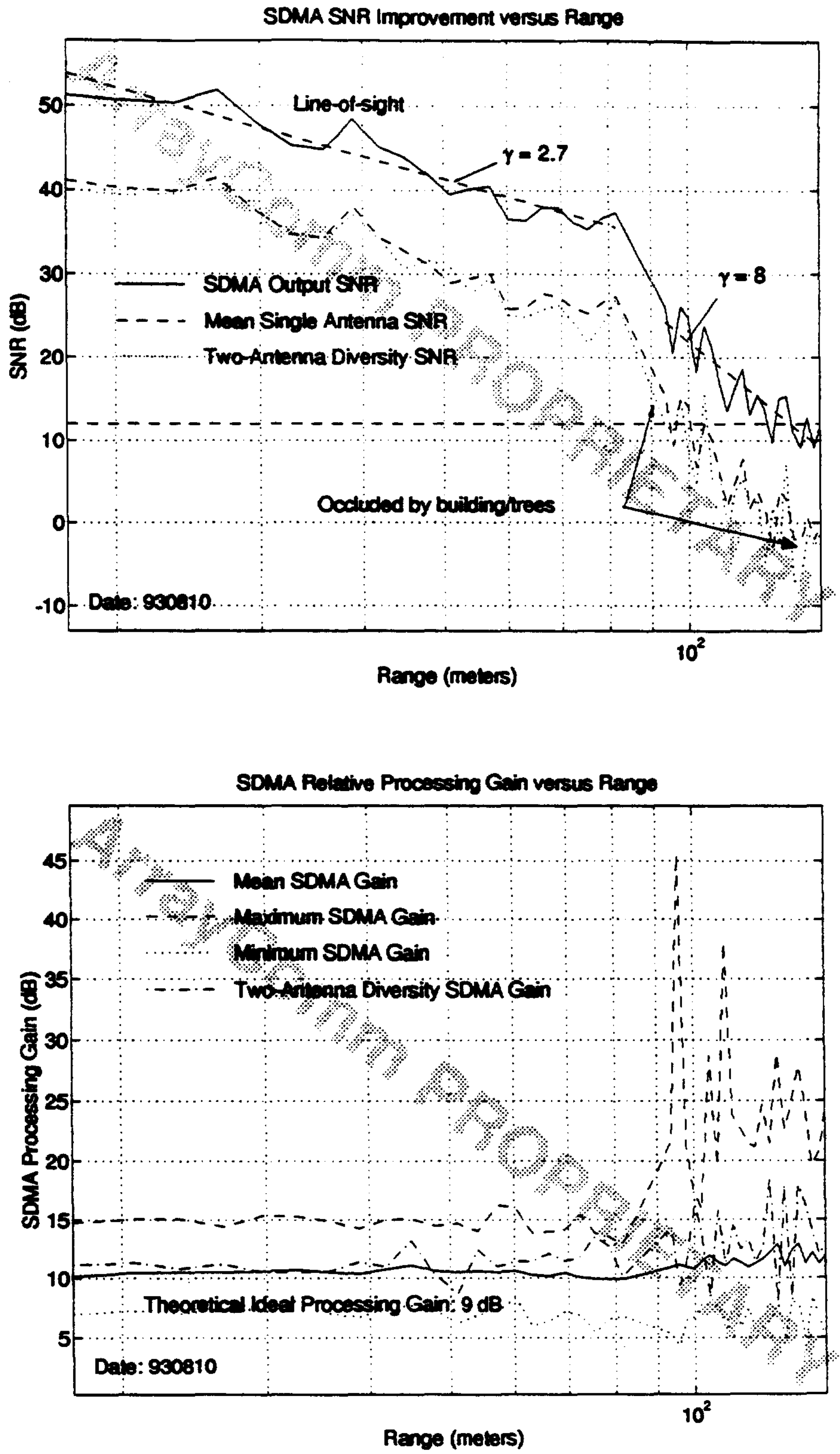


Figure 4-2: SDMA Signal Processing Gain over Conventional Single Antenna Output – Test 1

of tall pine trees, there was a large two-story commercial building occluding the line-of-sight. The results clearly indicate that the theoretical SDMA processing gain can be achieved in the presence of such occlusions.

A direct consequence of the processing gain achievable with SDMA is *range extension.* As is evident in Figure 4-2, at a demodulation threshold of 12 dB, the range of the cell was approximately doubled in the presence of a severe RF propagation loss factor ($\gamma \approx 8$). While the output of the mean or diversity receiver drops below 12 dB, which is for the purposes of this experiment set as the demodulation threshold, approximately 100 m from the array, the output of the SDMA processor is at or above that threshold to nearly 1.6 times that distance. Naturally, the amount of range extension depends on the propagation loss in a particular RF environment. For example, when the loss factor reduces to 2.7, the range can be more than doubled as is evidenced by choosing an appropriate threshold level (*e.g.,* 35 dB) in Figure 4-2.[2] Recall that for these experiments, both antennas were essentially at ground level which accounts for the more severe propagation loss than normally experienced in cellular operations. SDMA processing gain is still evident in spite of these effects however.

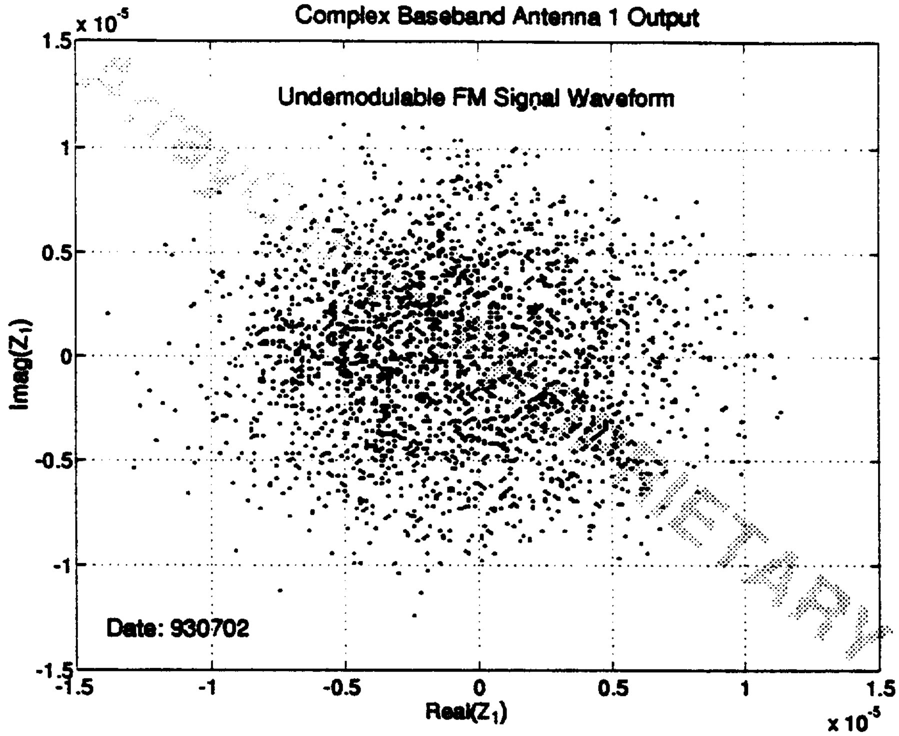
The ability to detect and demodulate substantially weaker signals than current single antenna systems is also demonstrated in Figure 4-3. There, the complex baseband output of a single element is compared to the complex baseband output of the SDMA spatial demultiplexer. For analog FM signals in the absence of noise, the corresponding output would be a perfect circle whose radius is the received signal level (*e.g.,* in volts). The time derivative of the angle of the complex signal is related to the transmitted voice waveform. When due to noise, the circle (eye diagram) *fills in*, the voice waveform can no longer be successfully recovered and the signal is lost. Clearly, the output of the conventional single antenna base station could not be demodulated, whereas the output of the SDMA processor was successfully demodulated.

4.5.2 SDMA Spatial Demultiplexing/Interference Rejection

To quantify SDMA's ability to spatially demultiplex and improve multiple waveforms, signals from four phones at spatially distinct angles were placed on the same frequency channel, and data were collected and analyzed. The ability of the SDMA processor to substantially reduce background noise and virtually eliminate cochannel interference is clearly manifest in Figure 4-4. Therein, received signal power (in dB relative units) is plotted for a single antenna element and, in the lower plot, for the output of all four (4) SDMA spatial demultiplexer outputs.

To elucidate the magnitude of the signal quality improvement, the phones were sequentially turned off and on under program control. During the first four 7 $msec$ intervals, each of the four signals was placed on air individually. Thus, the upper plot clearly shows the relative received power levels of each of the four signals individually. The relative powers vary over 15 dB. During the fifth interval, all four phones were transmitting simultaneously. The fact that the sum of four constant power (amplitude) signals is no longer constant amplitude is clearly seen in this interval in the upper plot. For the purposes of ascertaining the

[2] Such propagation factors are indicative of suburban and rural environments where larger coverage areas will be required for PCS systems to take hold worldwide.



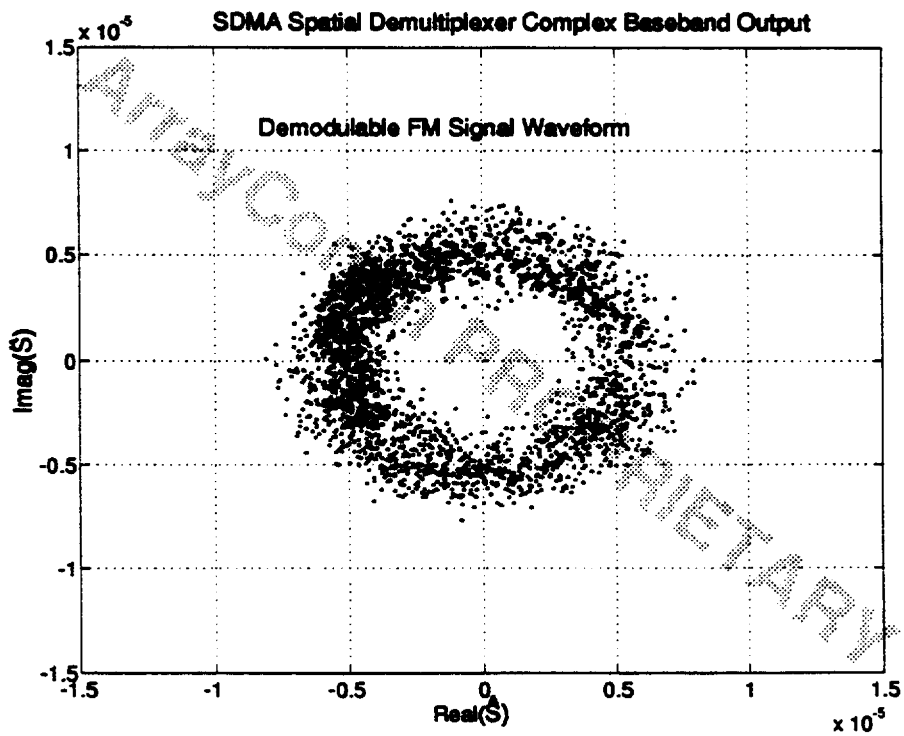


Figure 4-3: SDMA Spatial Demultiplexer Output SINR Improvement over Conventional Single Antenna Systems - Test 1

overall signal-to-noise ratio for each of the signals, the phones were all muted during the last interval.

In the upper plot, the power from a single element representing the output of a conventional base station is shown. When there is only one phone on the air (the first four 7 *msec* intervals), clean signals are received (recall AMPS FM signals are constant power waveforms). The single element SNRs range from 13 *dB* to 28 *dB*; the carrier-to-interference ratios (C/Is) (or signal-to-interference-plus-noise ratios – SINRs) range from -3 *dB* to -20 *dB*. During the interval in which all four phones were transmitting on the same frequency at the same time (the fifth interval), cochannel interference prevented successful reception of any of the signals. The received signal during that interval is no longer has constant amplitude. Finally, the -102 *dB* relative noise floor in each element is manifest in the last 7 *msec* interval.

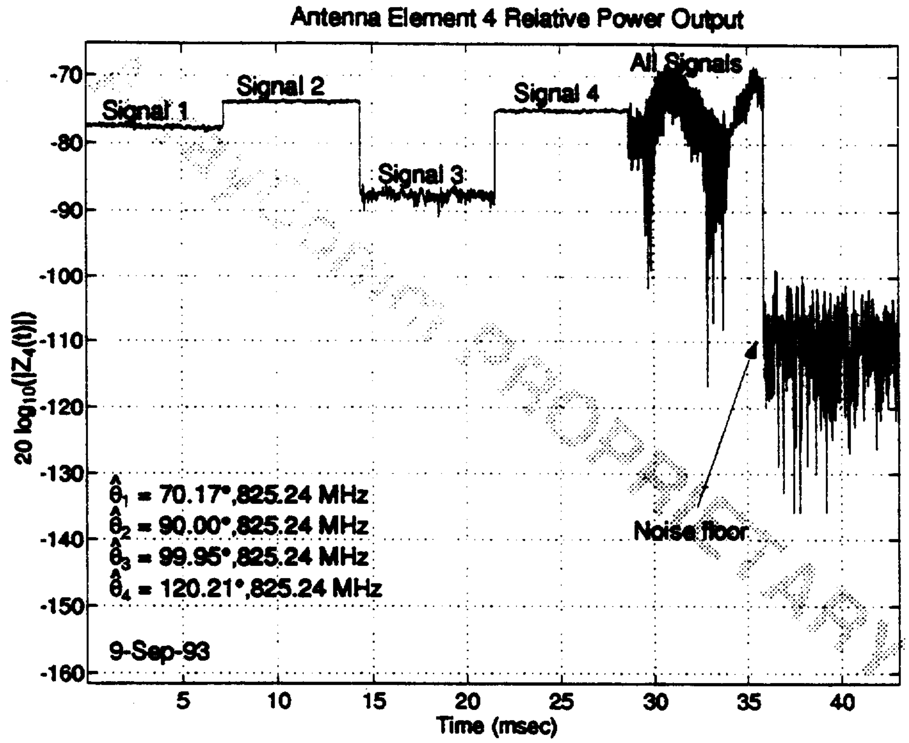
In the lower figure, the four outputs of the SDMA spatial demultiplexer are overlayed. Note that the noise floor has decreased by approximately 9 *dB* to -111 *dB* relative as predicted theoretically. Furthermore, as is clear from comparing the outputs during the fifth interval with each of the associated outputs in each of the first four intervals, the output SINRs for each of the demultiplexer outputs exceed the individual input signal SNRs by 9 *dB*. As predicted, the interference from the *other* three users has been removed from each of the spatial demultiplexer outputs and gain against background noise has been achieved as well. The maximum processing gain was achieved for the signal at 100° (interval 3) where a -20 *dB* processor input SINR was increased to $+22$ *dB* on output, an increase in excess of 40 *dB*.

4.5.3 SDMA Spatial Multiplexing/Directional Transmission

To demonstrate the ability of SDMA technology to directively transmit to specific users, several experiments were conducted. In the first experiment, a single phone was placed on the air. The unit was tracked by the SDMA processor, and the signal transmitted from the base station was focused by the SDMA spatial multiplexer toward the phone. An antenna and RF spectrum analyzer were used to measure the SDMA base station transmitted power at the associated transmit frequency as a function of angle at the same range and height as the phone.

The results are shown in the upper plot in Figure 4-5. The transmitted power is clearly focused in the direction of the mobile unit while the total transmitted power in all other directions is suppressed to the minimum possible with the antenna array employed. Note that the 3 *dB* width of the main lobe is approximately 14° as predicted by theory for an 8-element array with $\lambda/2$ element spacing steered to 0° from broadside. This clearly demonstrates the ability of the SDMA processor to direct a specific amount of energy at an intended target and simultaneously reduce the total amount of RF energy transmitted to the practical minimum.

To further demonstrate the ability of SDMA technology to directively transmit to selected users, two phones were placed on the air. The units were tracked by the SDMA processor, and the signals transmitted from the base station were focused by the SDMA spatial multiplexer toward the intended phones. Again, an antenna and RF spectrum analyzer were used to measure the SDMA base station transmitted power at the associated transmit frequency as a function of angle at the same range and height as the phones. The signal transmitted to



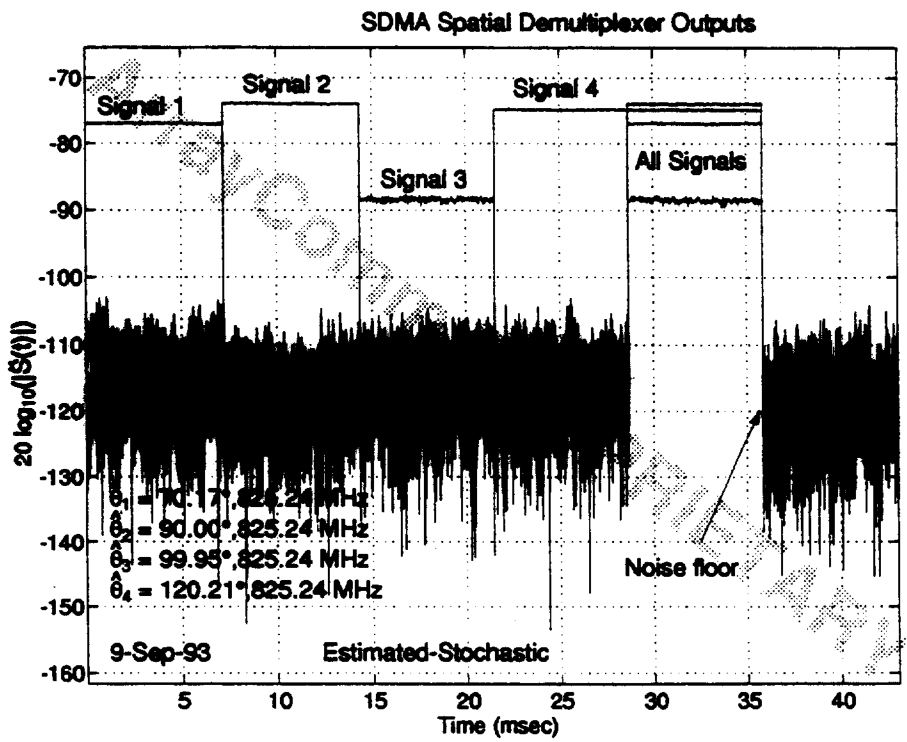
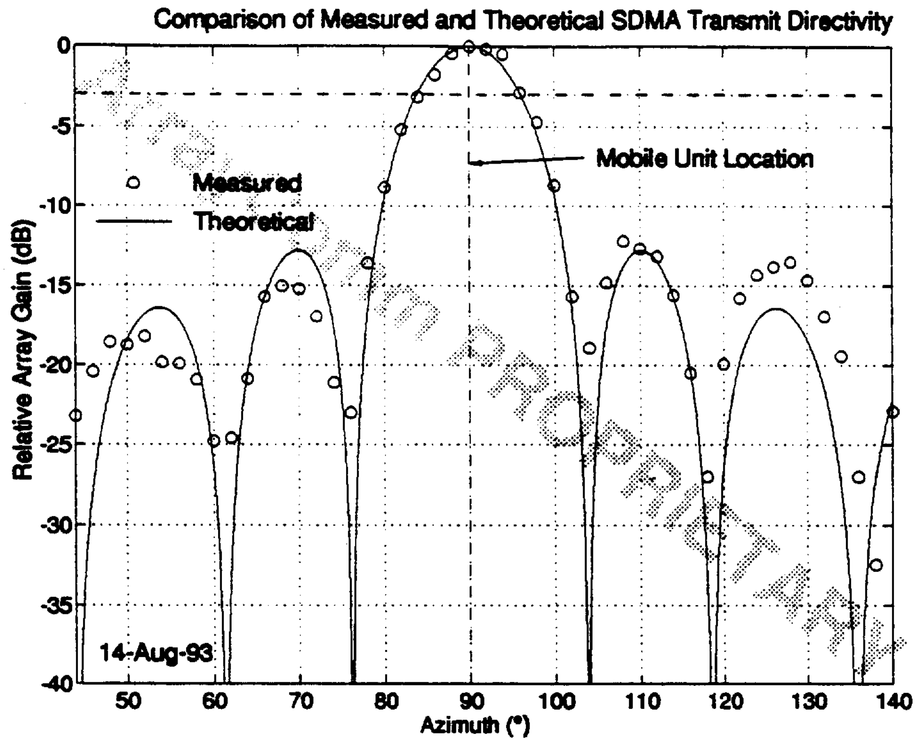


Figure 4-4: SDMA Signal Quality and Capacity Improvement over Conventional Single Antenna Systems - Test 1



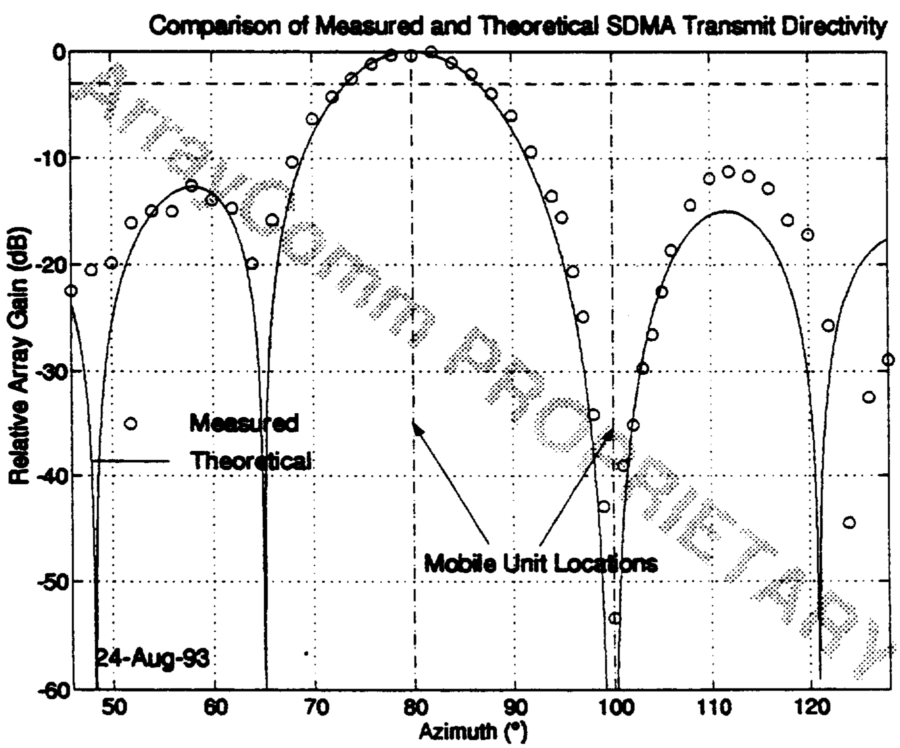


Figure 4-5: Measured and Theoretical SDMA Transmit Directivity - Tests 1 and 2

the unit at 100° was temporarily muted so that measurements of the directivity pattern of the signal transmitted to the phone at 80° could be made.

The results are shown in the lower plot in Figure 4-5. The transmitted power is clearly focused in the direction of the mobile unit at 80° while transmission of that signal toward the phone at 100° is suppressed, and the total power in all other directions is reduced to the minimum possible with the antenna array employed. This clearly demonstrates the ability of the SDMA processor to direct energy in specified directions to the exclusion of others. A similar pattern was achieved for transmission to the phone at 100°, thus demonstrating simultaneous transmission of different signals on the same frequency channel to users in different directions.

It is important to note that the user at 100° received essentially none of the RF transmission intended for the unit at 80°. While the user at 100° was being tracked by the processor, it is entirely possible to fix the direction of zero RF transmission. That is, it is possible to directively transmit to mobile users while simultaneously *not transmitting* in particular known directions so as not to interfere with the operations of other systems attempting to share the same frequency bands. This is extremely useful, for example, in coexisting with other users in the same frequency band, an important issue in the current PCS proceedings before the FCC. Using SDMA technology, it is possible to substantially reduce the amount of interference to microwave users without suffering large exclusion zones.

5. Summary and Conclusions

In summary, ArrayComm has successfully conducted initial on-air experiments of its SDMA technology. While the experiments did not involve any new modulation schemes (its SDMA technology is modulation independent), substantial increases in spectral efficiency were achieved through intelligent use of antenna arrays. SDMA base station transmit power levels were substantially below those used in current operational cellular systems during the initial testing. Standard portable units were kept at or near their lowest power settings and attenuators were used to simulate longer range. The ability to increase coverage area of SDMA base stations (with an eight-element antenna array) relative to conventional base stations by a factor of three to four was demonstrated. The ability to increase the capacity of a cell by a factor of four was also demonstrated; the theoretical maximum is one less than the number of elements.

Experimental determination of achievable SDMA processing gain was performed. Processing gain in excess of $10 \log_{10} M$ was demonstrated. In addition, the ability to substantially improve C/I ratios in interference limited systems such as the current AMPS cellular system was demonstrated. This processing gain provides increased SDMA base station coverage areas, lower handset powers, and higher data rates in digital transmission systems.

The ability to substantially reduce RF pollution resulting from omnidirectional transmission as currently employed in most wireless communication systems in existence today was demonstrated. Through directional transmission, communication from the SDMA base station to multiple portable units on the same frequency at the same time was achieved. This also provides SDMA base stations the ability to selectively isolate particular directions which are to be kept clear of RF transmissions in a particular frequency band. This allows